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OPEN-LOOP ANALYSIS OF AEROELASTIC FREQUENCY RESPONSE OF NREL 5.0 MW WIND TURBINE

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Introduction

Approach

Main body of abstract

<p>
Introduction</p>
<p>
The purpose of this work is to analyze the aeroelastic frequency response of a modern wind turbine from collective pitch demands and generator control actions to changes in rotor speed in open-loop.</p>
<p>
Predictions of the aeroelastic frequency responses from actuators to sensors are necessary for proper wind turbine control design. The controller must be designed based on a model that correctly predicts the aeroelastic response of the wind turbine to meet the objectives of the controller. Proper design of a wind turbine controller can reduce power variations and fatigue and extreme loads on components and thereby increase their lifetime. </p>
<p>
Control design for wind turbines is often done using linearized design models of low order. Bossanyi [3] has suggested appropriate complexity of models to be used for control design of a pitch-regulated, variable-speed wind turbine. When operating below the rated wind speed with generator torque control, it is suggested to use a model that contains at least the rotational dynamics of the drivetrain including the first torsional drivetrain mode. For above rated operation using collective pitch control it is suggested to model at least the rotor rotation, the torsional drivetrain dynamics, tower for-aft vibration and the dynamics of the pitch actuator. It is suggested to model aerodynamics using local gradients of the aerodynamic torque and thrust of the rotor.</p>
<p>
In this work, the open-loop aeroelastic frequency response functions from generator torque and collective pitch angle demand to rotor speed variations are estimated based on the recent linear aeroelastic model HAWCStab2 developed at Risø-DTU. The model is a linearization of a geometrically nonlinear finite beam element model coupled with an unsteady Blade Element Momentum model of aerodynamic loads including effects of dynamic stall. The model is currently being extended with the effects of dynamic inflow. Linearization is performed analytically around a stationary deflected state of the blades obtained from an equilibrium between elastic and centrifugal forces and the static aerodynamic loads due to an assumed uniform inflow to the rotor plane. Gravity forces are neglected to obtain this stationary steady operational state for any operational point given by a mean wind speed, pitch angle and rotor speed. The aeroelastic frequency response is computed for the NREL 5.0 MW [1] wind turbine in normal operation for selected wind speeds in the range 5-25 m/s. It is shown that the frequency responses are predicted well by the linear aeroelastic model when comparing with results obtained from time simulations using the nonlinear aeroelastic simulation model HAWC2 [2] with small control inputs. Errors on the predicted amplitudes are below 2 % for small amplitude excitation.</p>
<p>
Results</p>

<p>

The frequency response predicted by the linear model is found by applying a Laplace transformation on the linear system of equations followed by a matrix inversion. The frequency response predicted by time simulations using the nonlinear model HAWC2 is obtained by cutting out a controller once a stationary steady state is reached and then initiating harmonic actuator inputs with generator torque and collective pitch angle demands. A Fourier transformation is made on the time signals and the frequency response at the input frequency is extracted, whereby nonlinear effects and remaining transients are neglected.</p>

<p>

Figure 1 and 2 shows a comparison of the frequency response functions from variations in generator torque and collective pitch angle demands to rotor speed variations as predicted by the linear and nonlinear aeroelastic model. Comparison of frequency response is done for normal operation at 8 and 20 m/s. Figure 3 shows the errors on the amplitudes. The linear aeroelastic model does currently not include a model of the dynamic inflow, whereas dynamic inflow is included in the HAWC2 simulations. The error on low-frequency pitch excitation can be explained by the effects of dynamic inflow. There is good agreement between the linear and nonlinear model for small amplitude excitation. Dynamic inflow will be included in the results from the linear model before paper submission.</p>

<p>

The frequency response from generator torque to rotor speed variations is dominated by the effect of the aeroelastic mode shape with an aeroelastic frequency of 1.7 Hz that couples 1st torsional drivetrain mode with 1st symmetric edgewise blade mode. The response at low-frequency generator torque excitation is governed by the high rotational inertia of the entire drivetrain and rotor rotating in a solid-body rotation. At very low frequencies there is a clear difference in the frequency response for operation at 8 and 20 m/s, which is due to lower aerodynamic damping at 8 m/s of this solid-body rotation mode of the drivetrain and rotor. At 0.3 Hz there is resonance of the 1st tower side-side mode. Resonance of the 1st tower side-side mode only influences the response for frequencies 0.2 – 0.4 Hz due to a zero at 0.3 Hz close to the aeroelastic frequency of the tower mode. A zero exists at 0.6 Hz that results in low amplification between 0.5 – 0.7 Hz and a phase shift of +180 deg. The low amplification level makes it hard to control the rotor speed close to 0.6 Hz. The zero at 0.6 Hz is caused by the coupling between the 1st drivetrain mode and the solid-body rotor rotation mode.</p>

<p>

Figure 2 shows the open-loop aeroelastic frequency response from collective pitch angle demand to rotor speed variations. In these results it is assumed that the response of the actual pitch angle to a pitch angle demand input is the response of a second order filter with very high frequency. It is essential that the linearization is performed around a nonlinearly deflected state of the blades for correct prediction of the frequency response from pitch angle demand to rotor speed. In operation at 8 m/s the aerodynamic thrust is larger than at 20 m/s, resulting in larger nonlinear flapwise deflection and larger amplification at the aeroelastic frequency of the 1st drivetrain mode. The drop in amplitude at low frequencies for operation at 8 m/s can be explained by lower aerodynamic damping of the solid-body rotor rotation mode.</p>

<p>

Conclusions</p>

<p>

The open-loop aeroelastic frequency responses has been found from collective pitch angle demand and generator torque control signals to changes in rotor speed for the NREL 5.0 MW wind turbine in normal operation at 8 and 20 m/s. The frequency responses are predicted with the linear aeroelastic model of the new code HAWCStab2 and validated with the nonlinear aeroelastic model of HAWC2 [2]. The linear aeroelastic model can be used for design of model-based wind turbine controllers after order reduction has been applied. To correctly predict the frequency response from pitch angle demand to rotor speed, it is found to be important that linearization is performed around a nonlinear deflected blade. The frequency responses are seen to be mainly influenced by the solid-body rotor rotation mode, 1st drivetrain mode that couples with 1st symmetric edgewise blade mode and the 1st tower modes. The frequency response from generator torque to rotor speed variations is influenced greatly by a zero located at 0.6 Hz which exist due to a

coupling of the solid-body rotor rotation mode and the 1st drivetrain mode. Control of the rotor speed with generator torque close to 0.6 Hz will be difficult due to low amplification level.</p>
<p>
The final paper will include a discussion of the aeroelastic frequency responses from collective pitch angle demands and generator torque to rotor speed variations for normal operation at 5-25 m/s. The effects of dynamic inflow on the frequency responses will also be discussed.</p>
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Figure 1: Open-loop transfer function from generator torque to rotor speed variations. Comparison between aeroelastic response predicted using the nonlinear HAWC2 model and the linear HAWCStab2 model.</p>
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Figure 2: Open-loop transfer function from collective pitch angle demand to rotor speed variations. Comparison between aeroelastic response predicted using the nonlinear HAWC2 model and the linear HAWCStab2 model.</p>
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<p>
Figure 3: Error of amplitudes of rotor speed variations predicted from HAWC2 simulations and the linear aeroelastic HAWCStab2 model in percentage of rated speed.</p>

Conclusion